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STATIC AND DROP TESTS OF A QUARTER SCALE MODEL OF THE CC-115 AIRCRAFT EQUIPPED WITH AN AIR CUSHION LANDING SYSTEM

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SUMMARY

This work was performed by members of the Mechanical Branch, Vehicle Equipment Division, Air Force Flight Dynamics Laboratory. The work was accomplished under Program Element 62201F, Project 1369, and Task Area/Work Unit Number 136907/008.

Static load deflection tests and vertical drop tests were performed on a quarter scale model of a Canadian CC-115 (Buffalo) aircraft equipped with an Air Cushion Landing System (ACLS). The model weighed 610 lbs and the ACLS air supply was furnished by two electric fans.

The static load deflection tests showed that the model weight could be increased from 610 lbs to 1310 lbs before the fans stalled. The model deflected one inch when 560 lbs were added to it during hover over a solid surface. The portion of the weight supported by the trunk (instead of the cushion) increased from 3% at 610 lbs to 24% at 1310 lbs.

Six characteristic events were noted during the drop tests; (1) release (start of free-fall), (2) touch (model enters ground effect), (3) peak pressures, (4) peak loads at center of model, (5) fan recovery from stall (following a hard [redacted] landing), (6) top of bounce. The biggest difference between 10° nose up landings and level landings is that the cushion pressure peaks at event (4) instead of event (3).

Three critical landing conditions were observed: (1) The aft hard structure hit the landing surface when dropped at 10° pitch and a simulated 12.5 ft/sec full-scale sink speed. (2) When the hard structure did not hit, the peak vertical loads measured for a given sink speed occurred at 0° pitch and 7 1/2° instead of 0° roll (2.0 incremental g's were measured at a simulated 11 ft/sec). (3) The forward hard structure can hit the landing surface following a hard nose up landing and nose down rotation unless proper aerodynamic control is applied (since a -13° nose down pitch followed a 10° nose up landing).

The effects of the three initial conditions (drop height, pitch angle, and roll angle) were determined. Peak vertical loads of 2.6 g's (referenced to a zero g free-fall) were measured on all level drops which simulated a full-scale sink speed of 9.0 to 12.5 ft/sec. This result showed that the Air Cushion Landing System could efficiently absorb a high energy at a certain design load with a minimum stroke.

Publication

This Memorandum has been reviewed and is approved.

KENNERLY H. DIGGES, Chief
Mechanical Branch
Vehicle Equipment Division

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I. INTRODUCTION

A. What are Air Cushion Aircraft?

During hover and taxi, an aircraft equipped with an Air Cushion Landing System operates much like an air cushion surface vehicle. The development of modern air cushion vehicles began in the nineteen thirties. Large scale experimental and theoretical research did not begin until 1957. A flexible trunk is attached along the lower periohery of the vehicle and is usually used to distribute a peripheral jet of air created by an on-board fan. The trunk helps to contain the air cushion pressure which supports the weight of the vehicle.

Air Cushion Aircraft technology differs in several ways from that of air cushion surface vehicles. Landing systems are not designed to operate over rough seas as are most surface skimmers. Therefore, power requirements and daylight clearance in hover are less. Landing system designers must consider the unique problems of vertical energy absorption, inflight stowage of the trunk, rapid braking, power requirements during takeoff, aft trunk lubrication during takeoff rotation and initial landing impact, and minimum weight.

B. ACLS Development to Date

The limited work done to date on Air Cushion Landing Systems (ACLS) has already shown conclusively that this new concept can be used in place of the conventional wheeled gear used by aircraft. Studies began with an unsolicited proposal by Bell Aerososytems Company to the Air Force Flight Dynamics Laboratory (AFFDL). Contracted efforts started in February 1966 and the first ACLS takeoff and landing was accomplished on 4 August 1967. The AFFDL and Bell work is reported in References 1 through 5. Features of the concept were demonstrated using an LA-4 aircraft equipped with an ACLS. Taxi tests were made over ditches, tree stumps, step-terrain, and furrows. Takeoff and landing maneuvers were made over concrete and asphalt, and over unimproved surfaces including short and long grass, water, sand, and snow.

As a result of the success of these exploratory developments and initial flight demonstrations, the USAF and the Canadian Government have begun a joint advanced development program to equip a de Havilland CC-115 (Buffalo) aircraft with an ACLS. The first flight is planned for late 1972. Figure 1 shows the ACLS design for the CC-115 aircraft.

C. Scale Model of CC-115

The Bell Aerospace Company is using dynamic scale model testing to aid in the ACLS development for the CC-115 aircraft. A 1/4 and a 1/10 scale model are being used in static tests and in scaled forward velocity drop tests. These models are required to help verify the design. Purely analytical prediction of the ACLS energy absorption is difficult because the complex mechanism involves trunk deflections, transient increases in cushion and trunk pressures, forward and reverse flow through the fan, and variations in back pressure distribution for the many nozzles in the trunk

FIGURE 1. CC-115 AIRCRAFT EQUIPPED WITH ACLS

The 1/4 scale model used for the work described in this Memo is shown in Figure 2. The model is shown on the drop platform in the ACLS test cell at the AFFDL. The trunk is the original "short" configuration. This length has since been extended slightly aft. The view shown is from the forward, right hand side.

D. Scope of these Tests

Due to the limited time that the 1/4 scale model was available for these tests, the scope of this work was limited. The tests were all conducted during an unscheduled work delay at the contractor's plant, during which it was decided to keep the model in use by testing at the AFFDL. The model arrived at the AFFDL on 3 June 1971. The model was delivered back to Bell Aerospace Co. in Buffalo, New York, on 19 July 1971.

Approximately four of the six weeks were spent in preparing for the tests. Electrical power and voltage control had to be provided in the newly acquired ACLS test cell location. Data recording equipment had to be made compatible with the transducers and accelerometers on the model. A new release mechanism was required to drop the model. High speed films were taken of the drop tests and data for static and drop tests was recorded with an oscillograph. All static and dynamic measurements were made during a two week period.

II. TEST EQUIPMENT

A. Test Platform

This platform has a removable 2 by 3 foot center which allows the cushion pressure to escape when removed. One quarter of the table surface is one inch plexiglass (See Figure 2.).

B. Honeywell, 906A, Visicorder

This recorder was supplied with high sensitivity galvometers and was used to record up to 11 channels of data.

C. Sanborn - Model 60-1300

This recorder had a 2,000 pound load cell and was used to determine initial weight. Additional weights were 50 lb lead weights and 10 lb shot bags.

D. Manometer

A 40 inch water Manometer was used in calibrating the pressure transducers.

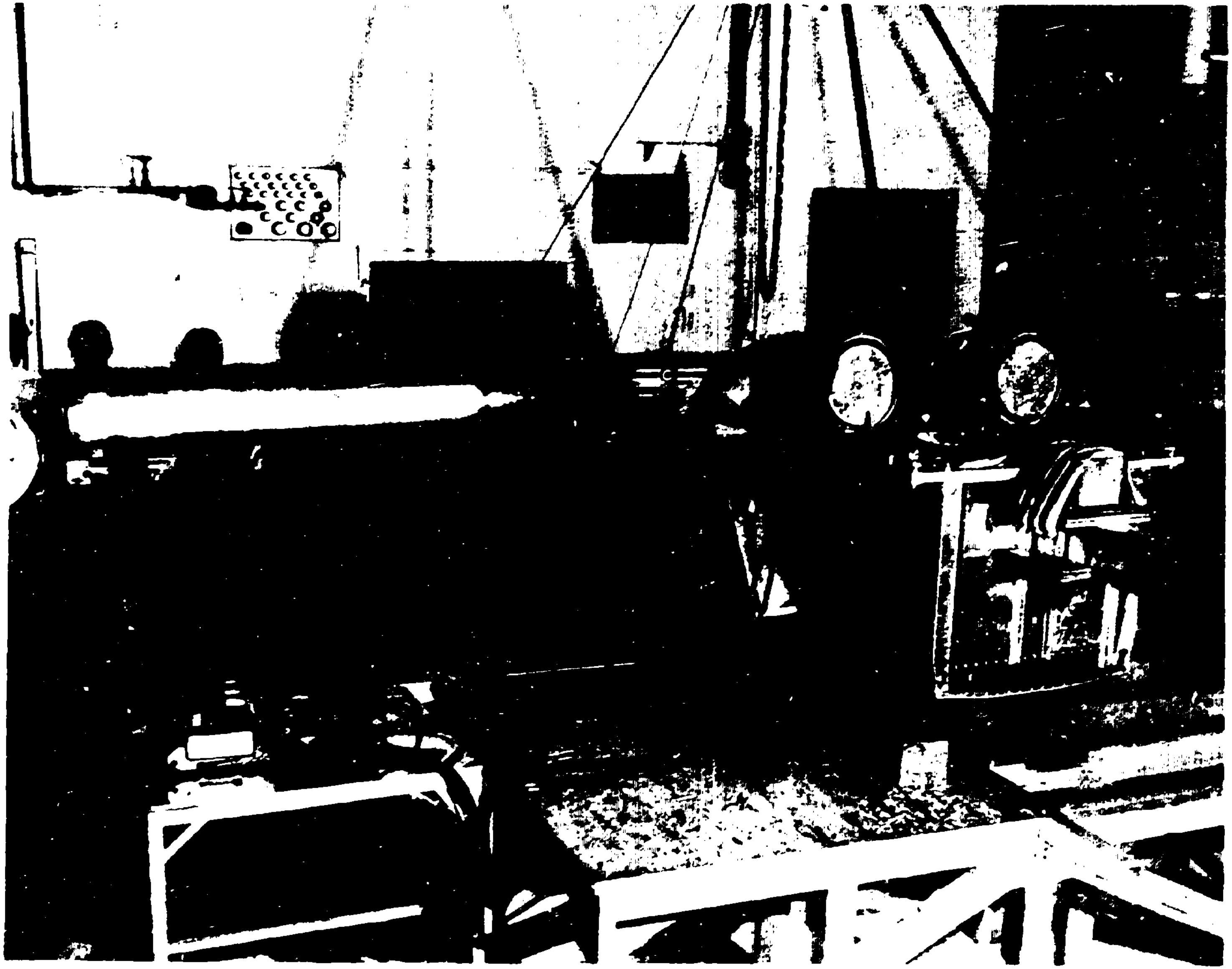

FIGURE 2. QUARTER SCALE MODEL ON DROP PLATFORM AT AFFDL.

E. Power Supply

The AC power supplied to the two baffled joy fan-motors was 200 volts, three phase, 400 cycles. The power was monitored and controlled at the test location, although the source was located in an adjacent building. The fans usually drew from 55 to 70 amps, depending on the loading conditions.

III. STATIC TESTS

A. Model Scaling Measurements

Based on dimensional analysis for a constant Froude number ($v^2/a\ h$) and a constant linear accelerationfield, the necessary scaling factor (function of λ) can be determined for a scaled model to have geometric and dynamic similarity. This is the type of scaling used for the 1/4 scale model. The scaling factors for ACLS are shown in Table 1.

Using these scaling factors, the necessary values for the 1/4 scale model of the CC-115 aircraft were calculated. These required values, along with certain measured values, are shown in Table 2. The aircraft weight distribution normally used for the 1/4 scale model is with center of gravity at 25% mean chord.

B. Static Load-Deflection Tests

(1) Test Plan.

The static load-deflection tests gave useful data about the model characteristics. The tests were performed by adding weights to the model as it hovered, and by measuring deflection and pressure changes.

The model was received with a one-way flow diaphram installed in the trunk. The intended function of this diaphram was to allow flow from the forward portion of the trunk to the aft section, but not the reverse. This would allow a more rapid rise in aft trunk pressure when the aircraft landed nose up. This diaphram was a variation from the CC-115 baseline design which was considered but not selected. The initial test plan was to do all testing with the diaphram installed. Two static load-deflection tests were run with the diaphram installed. One test was with weights added to the center of pressure (model remained level) and the other test was with weights added to the center of gravity (model nose high). It was found, however, that the diaphram was not functioning as intended. The aft trunk pressures were found to be 12 to 19% less than the forward trunk pressures as the model weight varied from 610 to 1210 lbs. This meant that the aft trunk flow was being restricted at the diaphram instead of at the aft trunk orifices. The remaining load-deflection and drop tests were therefore conducted with the diaphram removed.

QUANTITY	FULL-SCALE VALUE	SCALE FACTOR	MODEL VALUE
length, width, perimeter, height	L	λ	λ L
linear acceleration	a	1	a
force	F	λ^3	$\lambda^3 F$
moment of inertia	I	λ^5	$\lambda^5 I$
mass, weight	m	λ^3	$\lambda^3 m$
time	t	$\lambda^{1/2}$	$\lambda^{1/2} t$
speed	v	$\lambda^{1/2}$	$\lambda^{1/2} v$
angular acceleration	α	λ^{-1}	λ^{-1} α
pressure	P	λ	λ P
area	A	λ^2	λ^2 A
power	hp	$\lambda^{7/2}$	$\lambda^{7/2} hp$
pressure ratio	P_1/P_2	1	P_1/P_2
flow	Q	$\lambda^{5/2}$	$Q^{5/2}$
Reynolds number	R_e	$\lambda^{3/2}$	$\lambda^{3/2} R_e$
volume	V	λ^3	λ^3 V

*For example, a 1/4 scale model requires that λ = 1/4

Table 1. SCALING FACTORS FOR ACLS

QUANTITY	UNITS	SYMBOL	CC-115 DESIGN VALUE	SCALE FACTOR	REQUIRED 1/4 SCALE VALUE	MEASURED VALUE
OVERALL TRUNK						
LENGTH	ft, in.	L_t	30.7 ft.	λ	91.5 in.	92.5 in.
WIDTH	ft, in.	W_t	13.7 ft.	λ	41.1 in.	38. - 41. in.
STRUCTURAL HEIGHT	ft, in.	h	3.38 ft.	λ	10.13 in.	9 3/8 in
TRUNK GROUND TANGENT						
LENGTH	ft, in.	Lc	27.87 ft.	λ	83.6 in.	80.0 in.
WIDTH	ft, in.	W_c	9.75 ft.	λ	29.2 in.	24. - 29 in.
RADIUS	in.	R_c		λ		
LANDING WEIGHT	lbs.	W_a	39,100	λ^3	611.	13. in.
TRUNK PRESSURE	psf	P_t	342.	λ	85.5	610.
CUSHION PRESSURE	psf	P_c	171.	λ	42.75	83.5
P_c WITH BRAKES ON	psf		55.	λ	13.75	44
CUSHION AREA	ft^2	A_c	230.	λ^2	14.375	
BRAKE CONTACT/PILLOW	in^2	A_B	250.	λ^2	15.61	13.5
PILLOW AREA/PILLOW	in^2	A	1040	λ^2	65	74.25
BRAKE VENT AREA/SIDE	ft^2, in^2	A_{vent}	2.5 ft	λ^2	22.5 in^2	
TOTAL FLOW	ft^3/sec	Q	1910.	$\lambda^{5/2}$	59.6	50.
TRUNK VOLUME	ft^3	V_t	1090.	λ^3	17.	
CUSHION VOLUME	ft^3	V_c	239.6	λ^3	3.74	
MOMENTS OF INERTIA						
PITCH	slug ft^2	I_{yy}	280,780	λ^5	274.2	
ROLL	slug ft^2	I_{xx}	223,846	λ^5	218.6	
YAW	slug ft^2	I_{zz}	403,048	λ^5	413.	
PRESSURE RATIO		P_c/P_t	0.5	1	0.5	0.527
STOL LANDING SPEED	kts, fps	V_{land}	67 - 75 kts	$\lambda^{1/2}$	113 - 126 fps	N/A
FAN hp TOTAL	hp	hp_{fan}	1600.	$\lambda^{7/2}$	12.6	17.15
MAX. SINK SPEED	fps	v_{sink}	12.5	$\lambda^{1/2}$	6.25	N/A
MAX. AIRCRAFT g's	g	$g_{max.}$	2.5	1	2.5	N/A
DISTANCE c_p to c_g	in.			λ		7.5
AIR hp TOTAL	hp	hp air	1189.	$\lambda^{7/2}$	9.26	7.

TABLE 2. QUARTER SCALE MODEL MEASUREMENTS

The one-way diaphram was then removed and the load deflection tests again performed. All results reported here are for the diaphram removed and the weights added at the center of pressure (model level). Tests were conducted with the floor in and then repeated with the floor out (6ft vent area under model). The following measurements were made (calibrations included):

(1) model weight, w_a (lbs.)

(2) hard structure height above floor, h (inches)

(3) trunk pressure, P_t, (31 psf/inch)

(4) cushion pressure, P_c, (15.4 psf/inch)

(5) starboard diffuser static pressure, P_d, (32 psf/inch)

(6) port diffuser differential pitot head pressure, ΔP_d, (22 psf/inch)

In addition, sound readings were taken around the model. The highest readings were 120 db next to the model, and showed that ear protection was required. Noise throughout the test cell was 112 db. Noise outside the cell was 98 to 106 db. Noise in the adjacent cell was 82 db. Noise in the nearest offices was measured as 75 db, but did cause some complaints which indicated that long duration tests were not advisable during normal office hours.

(2) Results

The model weight, hard structure height, and four pressures were measured at these conditions: out of ground effect (OGE), at the first sign of cushion pressure increase (start of in ground effect (IGE), at the normal hover condition (610 lbs.), and then at additional 100 lb. increments until the fans stalled or the model was unstable. Two test series were conducted, one with floor in and one with floor out.

A summary of the results is given in Tables 3 and 4, and in Figures 3, 4, 5, and 6. Figure 3 shows the load-deflection characteristics with the floor in. The model was loaded from 610 to 1310 lbs. Above 1310 lbs, the trunk pressure (P_t) exceeded 105 psfg and the fan stalled. The pressure ratio (P_c/P_t) varied from 0.527 at the design weight (610 lbs.) to 0.715 at 1310 lbs. The hard structure height varied from 9 3/8 to 8 1/8 inches. As W_a increased, the air flow and the differential pressure (ΔP_d) always decreased, the trunk flattened, and P_c increased. The flow per fan is related to ΔP_d as follows (Reference 6):

$$Q = 4.65\sqrt{\Delta P_d} \qquad (ft^3/sec/fan)$$

If this equation is accurate for the model configuration tested, then the flow was lower than desired, while the power into the fans was high (Table 2).

Weight Lbs. W_a	Pressure P_t-Trunk PSF$_g$	Pressure P_c-Cushion PSF$_g$	Pressure P_d-Diff. PSF$_f$	Pressure ΔP_j-Diff. PSF$_f$	Height h -H.Etr. Inches	Calculated A_t-Trunk Ft2	Condition
610	63.3	1.075	88.3	26.6	15.625		CGE
610	64.8	6.63	88.5	25.7	10.5		Touch, IGE
610	83.5	44.0	102.0	24.2	9.375	0.19	IGE - Free Float
710	87.4	49.6	104.3	24.2	9.25	0.457	Increment Loading
810	90.0	54.6	106.1	23.3	9.0	0.80	" "
910	93.5	59.1	109.2	22.9	8.75	1.20	" "
1010	97.0	63.4	112.0	21.0	8.625	1.58	" "
1110	100.1	67.5	115.0	20.6	8.50	1.96	" "
1210	103.4	71.7	116.8	19.9	8.375	2.34	" "
1310	105.1	74.7	118.0	18.4	8.125	2.85	" "

TABLE 3. STATIC LOADING RESULTS (FLOOR IN)

Weight Wa Lbs.	Pressure P_t-Trunk PSFg	Pressure P_c-Cushion PSFg	Pressure P_d- Diff PSFg	Pressure ΔP_d-Diff PSFg	Height-h Structure Inches	Calculated A_t-Trunk-FP Ft^2	Condition
610	60.2	0.77	88.6	[illegible].6	17.5		OGE
610	80.4	0.77	101.5	24.4	10.5		IGE - Touch
610	80.0	1.08	99.0	24.4	8.25	7.44	Free Float
710	83.2	1.54	102.2	22.5	8.0	8.28	Increment Loading
810	85.3	2.31	104.5	21.4	7.75	9.14	" "
910	87.5	2.16	105.8	22.5	7.562	10.15	" "
1010	89.4	4.28	107.8	22.5	7.25	10.65	" "
1110	91.0	4.92	108.3	21.4	7.00	11.5[illegible]	" "
1210	9[illegible].0	4.28	108.0	22.3	6.75	12.80	" "

TABLE 4. STATIC LOADING RESULTS (FLOOR OUT)

FIGURE 3. PRESSURE ~ WEIGHT
(FLOOR IN)

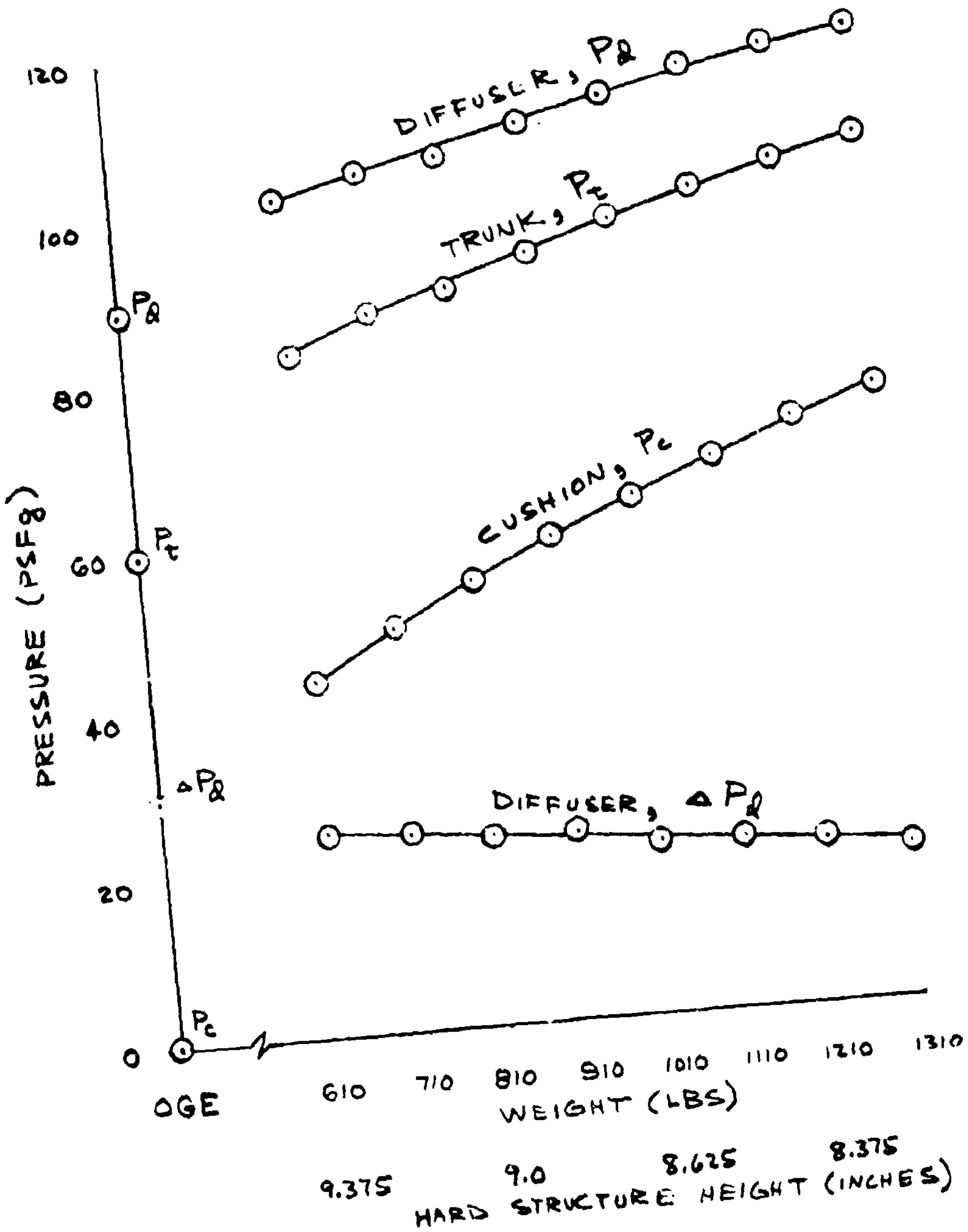

FIGURE 4. PRESSURE vs WEIGHT (FLOOR OUT)

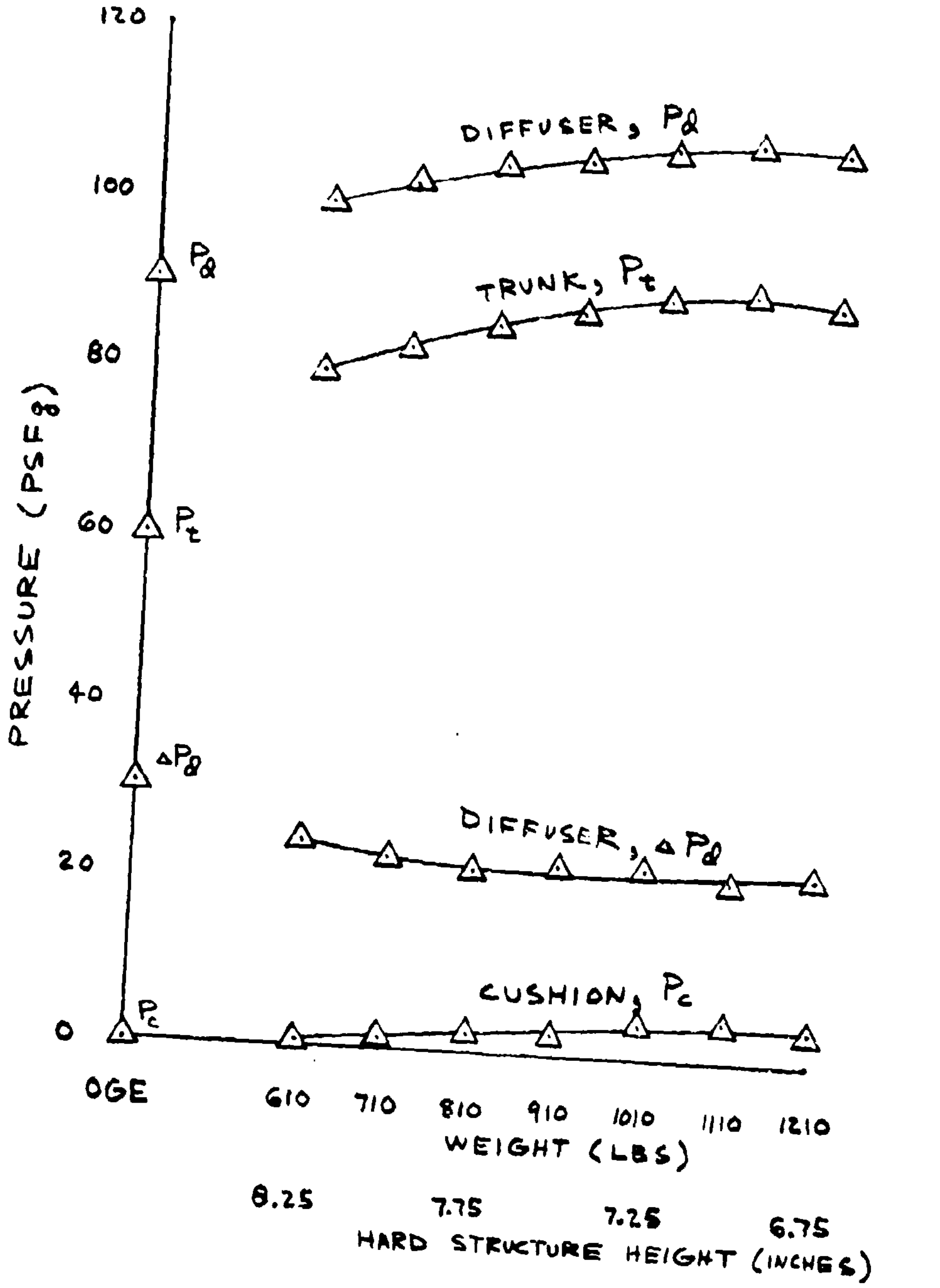

FIGURE 5. AREA OF TRUNK CONTACT vs HARD STRUCTURE HEIGHT

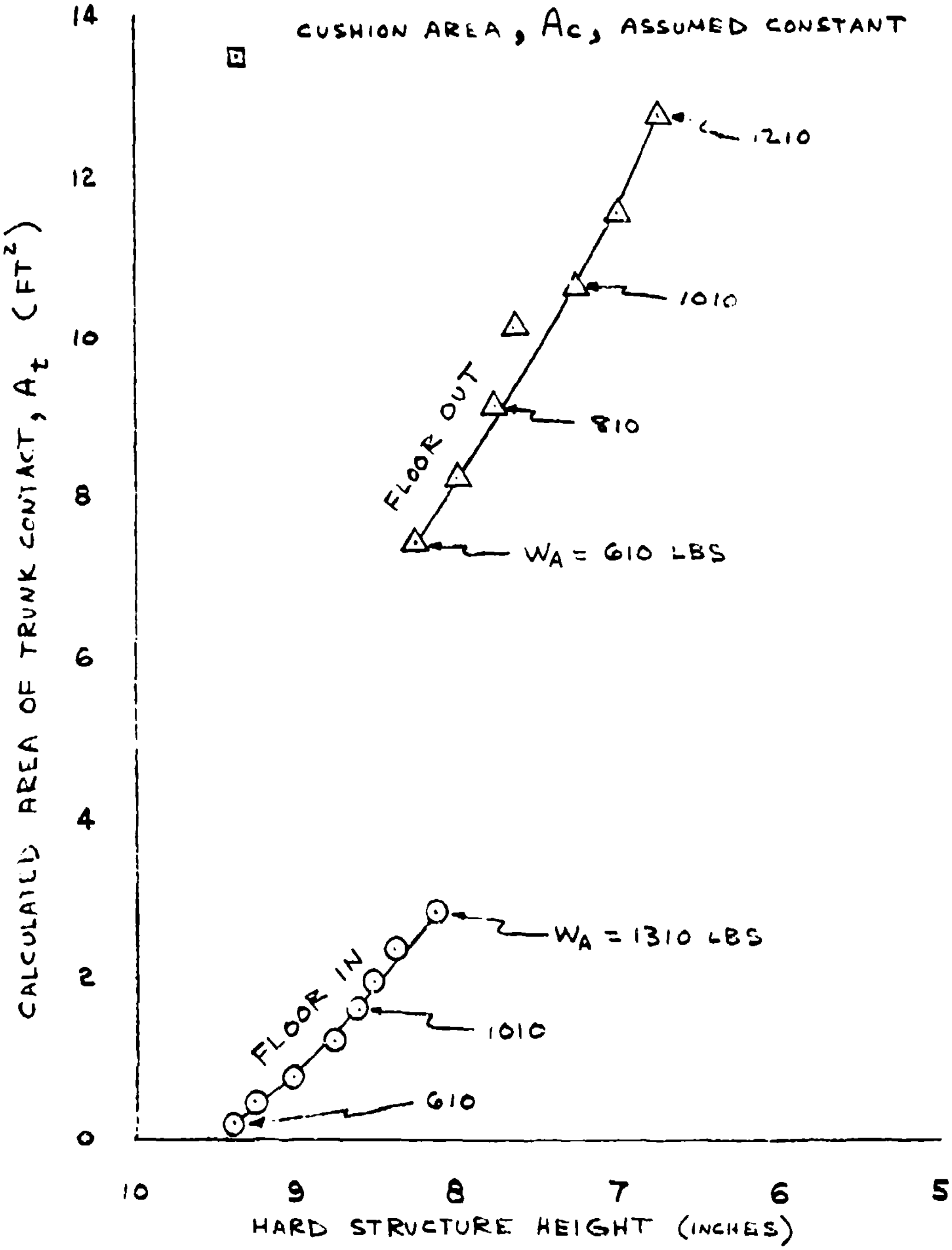

FIGURE 6. LOAD-DEFLECTION CHARACTERISTICS

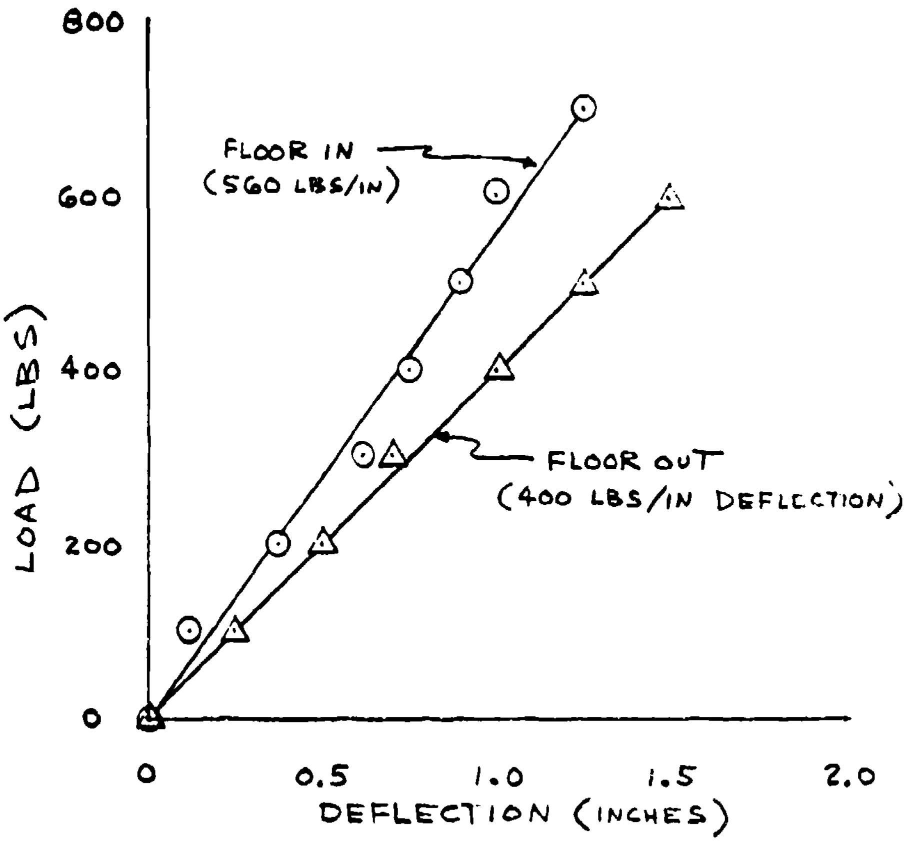

Figure 4 shows the load-deflection characteristics with the floor out ($6ft^2$ vent area under model). The model was loaded from 610 to 1210 lbs. Above 1210 lbs the trunk pressure was only 90 psfg and the fan did not stall -- but the model was so unstable that it could not be balanced out. The hard structure height varied from 8 1/4 (at 610 lbs) to 6 3/4 inches (at 1210 lbs.

An approximation of the area trunk pressure contact with the surface can be made by considering a vertical force balance. When the model is in hover and the vertical acceleration is zero, a vertical force balance for a level model gives:

$$W_a = P_cA_c + P_tA_t + L_{aero} + W_{brakes} + F_{jet}$$

If the brakes are not applied, then no weight is on the brakes and the last term (W_{brakes}) is zero. If there is no horizontal airflow over the model, then the aerodynamic life (L_{aero}) is zero. From previous studies (Reference 5) it has been shown that the pure jet thrust (F_{jet}) can usually be neglected. Dropping these last three terms and solving for the trunk pressure contact area:

$$A_t = \frac{W_A - P_cA_c}{P_t}$$

This equation was used to calculate the trunk contact area for each model weight. Here it was assumed that the model was supported by two forces, P_tA_t and P_cA_c. The area over which the trunk pressure acts is called the trunk contact area (A_t). The cushion area (A_c) was assumed to be constant at 13.5 ft^2.

Figure 5 shows how the calculated trunk contact area (A_t) varies with hard structure height with both the fl-or in and the floor out. At a height of 8 1/4 inches, A_t was significantly greater with the floor out (P_c = 1 psfg) than with the floor in (P_c = 73 psfg). This difference in maximum A_t was from 7 1/2 ft^2 with floor out to 3 ft^2 with floor in.

Although these reported tests were all conducted with weights added to the center of pressure (model level), previous tests with the one-way flow diaphram showed that the same A_t is calculated for a given model weight if the weights are added at the center of gravity (model nose high).

From Figure 5, it is apparent that as the model weight increases, the trunk flattens (A_t increases) and the trunk carries an increasing amount of load. Even with the floor in and the cushion area supporting a major part of the load, the trunk load increased from 3% to 24% of the total load as W_a increased from 610 to 1310 lbs. With the floor out, the trunk always supported 93% of the load.

Figure 6 shows the load-deflection characteristics with floor in and out. The model was stiffer with the floor in, requiring a 560 lb load for a one inch deflection. A 400 lb load gave a one inch [redacted] the
deflection with

floor out. The full-scale load-deflection should scale as λ^2. Therefore, the full-scale CC-115 should have load deflections of 16 times those given above, or 8960 and 6400 lbs/inch, respectively. The stiffness of the air spring on a conventional C-119 shock strut is around 4500 lbs/inch (Reference 5).

For all tests, the daylight clearance between the bottom of the trunk and the floor was between zero and 1/4 inch. The 1/4 inch clearance was only noted at 610 lbs and even here, the trunk irregularities caused the clearance to be essentially zero in various places. All weights above 710 lbs had maximum clearances of less than 1/8 inch.

At the design weight of 610 lbs, the electric fans drew over 17 hp (70 amps), but the total air horsepower was only 7 hp as calculated from:

$$h_p \text{ air} = \frac{P_t \quad Q}{550}$$

where total $Q = 9.3\sqrt{\Delta P_d}$

IV. VERTICAL DROP TESTS

A. Test Plan

The model was dropped from various heights and at various attitudes to determine its vertical dynamic response. Twelve drop tests were conducted (Table 5) with the drop platform floor in and the trunk's one-way flow diagram removed.

The weight distribution at 610 lbs was such that the model was level during equilibrium hover. The 80 lb weight required to raise the model weight from 530 lbs to 610 lbs was added forward of the fans (as shown in Figure 2 of Reference 6) in order to level the model. This was a variation from the aircraft design which hovers nose up (center of pressure forward of center of gravity). The model was therefore not completely, dynamically similar. For example, a level drop (zero pitch and roll angle) resulted in an upward bounce with negligible angular pitch acceleration on the first bounce following a level drop.

The model was also not dynamically similar because it lacked an elastic trunk and flow trim valves. An elastic trunk was not used because no material was available with the necessary scaled load-elongation characteristics. Flow trim valves could have been included, but were not. The function of the flow trim valves is to close when out of ground effect (OGE) and therefore keep the trunk pressure at the design level (342 psfg full scale or 85.5 psfg quarter scale). When the aircraft lands, the trim valves open and expose more trunk vent area to the cushion pressure. These drop tests were conducted with the vent holes open, therefore, the OGE trunk pressure was about 68 psf instead of 85 psf -- but all bounces after the first bounce were with the correct vent area.

Eleven parameters were measured as shown in Table 6. Roll and pitch attitude were not recorded on all tests.

No wing lift mechanism was used, therefore, the model was in free-fall from release to touch. The effect of no wing lift is clear by comparing the results of the movies of the Bell tests versus these tests. The most noticeable difference is during a nose up landing. The model completely leaves the surface between bounces on the aft and forward trunk when full wing lift is applied. Without wing lift, the model never, completely leaves the surface after first hitting it.

B. Results

The results of the drop tests are given in Tables 7 through 13. The oscillograph records for runs 3, 4, 9, 10, and 12 were ruined at Tech Photo while undergoing a "permatizing" process. Therefore, permanent records are only available for tests 1, 2, 5, 6, 7, 8, and 11. High speed movies were taken of all drop tests. The drop height shown in Table 5 was calculated as the height required for a solid object to reach the desired sink speed at impact. The test drop heights were measured from the floor to the lowest

TEST NUMBER	V_{SINK} DESIRED [*2] (ft/sec)	DAYLIGHT CLEARANCE DROP HEIGHT (inches)	PITCH ANGLE (degrees)	ROLL ANGLE (degrees)
1	6.25	7.28	0	0
2	5.5	5.64	0	0
(3) [*1]	6.0	6.71	5	0
(4)	6.25	7.28	10	0
5	6.25	7.28	10	0
6	6.25	7.28	10	7 1/2
7	5.5	5.64	0	7 1/2
8	4.5	3.77	0	0
(9)	3.5	2.285	0	0
(10)	6.0	6.71	10	0
11	4.5	3.77	10	0
(12)	5.5	5.64	5	0

*Notes 1. data lost for tests 3, 4, 9, 10, and 12.

2. full-scale simulated V_{sink} is twice this test value

Table 5. DROP TEST PLAN

CHANNEL	SYMBOL	PARAMETER (units)	CALIBRATION FACTOR FOR CERTAIN DEFLECTIONS ON VISICORDER
1	P_t	forward trunk pressure (psfg)	31.22 psfg/inch
2	P_c	aft cushion pressure (psfg)	25.68 psfg/inch
4	P_d	PORT diffuser static pressure (psfg)	31.7 psfg/inch
5	ΔP_d	STARBOARD diffuser differential pitot head pressure (psfg)	26.2 psfg/inch
7	$g_{c.g.}$	vertical g load at center of gravity (c.g.)	0.85 inches/g
8	g_{fwd}	vertical g load forward of c.g.	0.66 inches/g
9	ϕ	roll attitude (degrees)	0.22 inches/degree
10	Θ	pitch altitude (degrees)	0.184 inches/degree
11	g_{port}	vertical g load on port side of c.g.	1.1 inches/g

Table 6. DROP TEST MEASUREMENTS

portion of the undistorted trunk. The equation used to calculate the drop height for a test was a function of the desired sink speed (ft/sec):

$$\text{drop height (inches)} = \frac{12}{(2)(32.17)} v_{sink}^2$$

The desired v_{sink} for the quarter scale model is half the v_{sink} that is being simulated for the full scale aircraft (See Table 1.)

High speed black and white movies were taken of each drop test from the port side and from the forward starboard side.

(1) Level Drop Test Results.

Tests 1, 2, and 8 were all level drops (zero degrees pitch and roll) made from different drop heights (7.28. 5.64, and 3.77 inches, respectively).

All three tests showed the same characteristic oscillograph traces for each of the four pressures and three accelerations that were recorded. Figure 7 shows the oscillograph record for the first bounce of Test Number 8. Six characteristic events were noted. Figure 8 shows the full scale details of the peak pressure and load traces for Test 8. Since the center of gravity was placed at the center of pressure for these tests, the model bounced straight up and came down for repeated level landings until it remained in ground effect. Therefore, the six events noted in Figure 7 were repeated for several bounces on all three level drop tests.

The six characteristic events noted for all level landings were:

(a) Release -- is when the three accelerations rapidly change from 1g to zero g.

(b) Touch -- is when the diffuser pressure (P_d) started to rise from its out of ground effect value.

(c) Peak pressures -- for level drops occurring at the nominal time when three pressures (P_t, P_c, and P_d) reached peak highs and the differential pressure, ΔP_d, reached a peak negative value (indicating maximum reverse flow). The forward acceleration, g_{fwd}, also always reached its maximum at this time. All of these five events occurred within less than a 0.01 second interval. The cushion pressure peaked first and the trunk pressure peaked last. The peaks for g_{fwd}, P_d, and ΔP_d occurred about halfway between the P_c and P_t peaks.

DROP TEST NO. 1

INITIAL CONDITIONS drop height 7.26"; pitch angle 0°; roll angle 0°

Condition	Pressure P_t psf	Pressure P_c psf	Pressure P_d psf	Pressure ΔP_d psf	Accel. g center	Accel. g fwd	Accel. g port	Time Seconds
Release	68.	0	86.	28	0.0	0.0	0.0	0.00
Touch	70.	17.	90.	28	0.2	0.3	0.1	0.15*
Peak Pressures	200	149	155	-48.	2.1	2.5	2.5	0.21
Peak Center Load	73.	111	97*	5	2.4	2.0	2.5	0.24
Fan Recovery	[illegible]	126	112	40	2.0	2.1	2.3	0.36
Top of bounce	68.	6	90	29	0.0	0.2	0.0	0.55

(*Min. P_d was 48 psfg at 0.3 sec.)

Note: This was the only run that oscillograph paper speed was erratic. It appeared to start out at 33 inches/sec instead of 50 inches/sec.

Table 7.

DROP TEST NO. 2

INITIAL CONDITIONS drop height 5.64"; pitch angle 0°; roll angle 0°

Condition	Pressure P_t	Pressure P_c	Pressure P_{ℓ}	Pressure ΔP_d	Accel. g cg	Accel. g fwd	Accel. g port	Roll ϕ Degrees ↓	Pitch θ Degrees ↓	Time Seconds
Release	68	0	88	28	0.0	0.0	0.0			0.0
Touch	73	30	93	30	0.3	0.3	0.8			0.16
Peak Pressures	203	172	160	-47	2.5	2.7	2.5			0.21
Peak Center Loads	98	126	102*	-8	2.6	2.1	2.5			0.23
Fan Recovery	120	136	115	37	2.1	2.1	2.3			0.36
Top of Bounce	70	4	91	29	0.0	0.2	0.0			0.52

*min P_d was 5.5 psfg at 0.31 sec.

Table 8.

DROP TEST NO. 5

INITIAL CONDITIONS Drop Height 7.28"; Pitch Angle 10°; Roll Angle 0°

Condition	Pressure P_t Psf	Pressure P_c Psf	Pressure P_d Psf	Pressure ΔP_d	Accel. g_{cg}	Accel. g_{fwd}	Accel g_{port}	Roll ϕ degrees	Pitch θ degrees	Time Seconds
Release	68	0	90	30	0.0	0.0	0.0	0	not recorded	0.00
Touch	69	6	92	30	0.3	0.3	0.2	2		0.19
First Peak P_t	138	15	124*	19	1.6	1.0	1.6	3		0.26
**see note	82	15	73	-6	5.5	2.7	6.0	3		0.30
Peak Loads	45	23	51	0	3.5	2.0	3.5	4		0.34
Fan Recovery	125	82	118	35	3.5	3.0	3.6	4		0.39
Top of Bounce	70	0	93	31	0.0	0.7	0.0	6		0.72

*dropped rapidly to 100 psf and reached min of 52 psfg at 0.33 sec.

** Aft hard structure of model hit floor

TABLE 9

DROP TEST NO. 6

INITIAL CONDITIONS Drop Height 7.28"; Pitch Angle 10°; Roll Angle 7 1/2°

Condition	Pressure P_t	Pressure P_c	Pressure P_d	Pressure ΔP_d	Accel. g_{cg}	Accel. g_{fwd}	Accel. g_{port}	Roll ϕ degrees	Pitch θ degrees	Time Seconds
Release	68	0	90	29	0.0	0.0	0.0	+7 1/2	not recorded	0.00
Touch	68	5	90	30	0.4	0.4	0.3	+7 1/2		0.19
First Peak P_t	145	12	122*	-15	1.5	1.0	1.5	+8		0.26
Peak Loads	112	60	114	29	2.7	3.0	3.3	+6		0.38
Fan Recovery	**									0.38
Top of Bounce	68	0	95	29	0.0	0.2	0.0	+3***		0.68

*min P_d was 45 psf at 0.32 sec.

**Fan recovered during peak loads

***Roll angle passed through 0° at 1.80 seconds after release

TABLE 10

DROP TEST NO. 7

INITIAL CONDITIONS drop height 5.64"; pitch angle 0°; roll angle 7 1/2°

Condition	Pressure P_t psf	Pressure P_c psf	Pressure P_d psf	Pressure ΔP_d psf	Accel. g cg	Accel. g fwd	Accel. g port	Roll ϕ Degrees ↓	Pitch Θ Degrees ↓	Time Seconds
Release	68	0	90	29	0.0	0.0	0.0	7 1/2	erratic	0.00
Touch	68	8	90	29	0.2	0.4	0.0	8		0.17
First Peak P_t	180	150	146	-44	2.5	2.6	2.1	7		0.25
Peak Loads	135	135	124*	[illegible]	3.0	2.9	3.0	7		0.26
Fan Recovery	115	105	105	29	1.9	2.1	1.7	8		0.38
Top of Bounce	68	3	90	29	0.3	0.4	0.2	7 1/2**		0.83
			*min P_d was 40 psfg at 0.32 sec							

** Roll Angle passed through 0° at 1.10 second after release.

Table 11

DROP TEST NO. 8

INITIAL CONDITIONS drop height 3.77"· pitch angle 0°; roll angle 0°

Condition	Pressure P_t psf	Pressure P_c psf	Pressure P_d psf	Pressure ΔP_d psf	Accel. g cg	Accel. g fwd	Accel. g port	Roll ϕ degrees ↓	Pitch θ degrees ↓	Time Seconds
Release	68	0	90	29	0.0	0.0	0.0			0.00
Touch	68	8	90	29	0.2	0.3	0.2			0.14
Peak Pressures	190	165	152	-40	2.2	2.4	2.2			0.19
Peak Center Loads	80	95	99*	2	2.9	2.1	2.7			0.22
Fan Recovery	110	115	117	24	2.1	2.1	2.4			0.33
Top of Bounce	70	2	90	28	0.0	0.2	0.0			0.50
			* min P_d was 47 psfg at 0.28 sec							

Table 12

DROP TEST NO. 11

INITIAL CONDITIONS Drop Height 3.77"; Pitch Angle 10°; Roll Angle 0°

Condition	Pressure P_t	Pressure P_c	Pressure P_d	Pressure ΔP_d	Accel. g_{cg}	Accel. g_{fwd}	Accel. g_{port}	Roll ϕ degrees	Pitch θ degrees	Time Seconds
Release	68	0	90	29	0.0	0.0	0.0	0	+10	0.00
Touch	68	3	92	31	0.1	0.2	0.0	0		0.14
First Peak P_t	126	15	125	20	1.5	1.1	1.5	0		0.22
Peak Loads	131	112	115*	-5	2.5	2.7	2.6	0	5	0.31
Fan Recovery	120	107	111	29	2.3	2.4	2.2	-1	-2	0.43
Tcp of Bounce	75	0	98	29	0.3	0.7	0.4	+1	-7	0.63
Maximum Pitch	90	0	110	32	0.6	1.0	0.7	-3	-13	0.77

*min P_d was 50 psff at 0.38 se.

TABLE 13

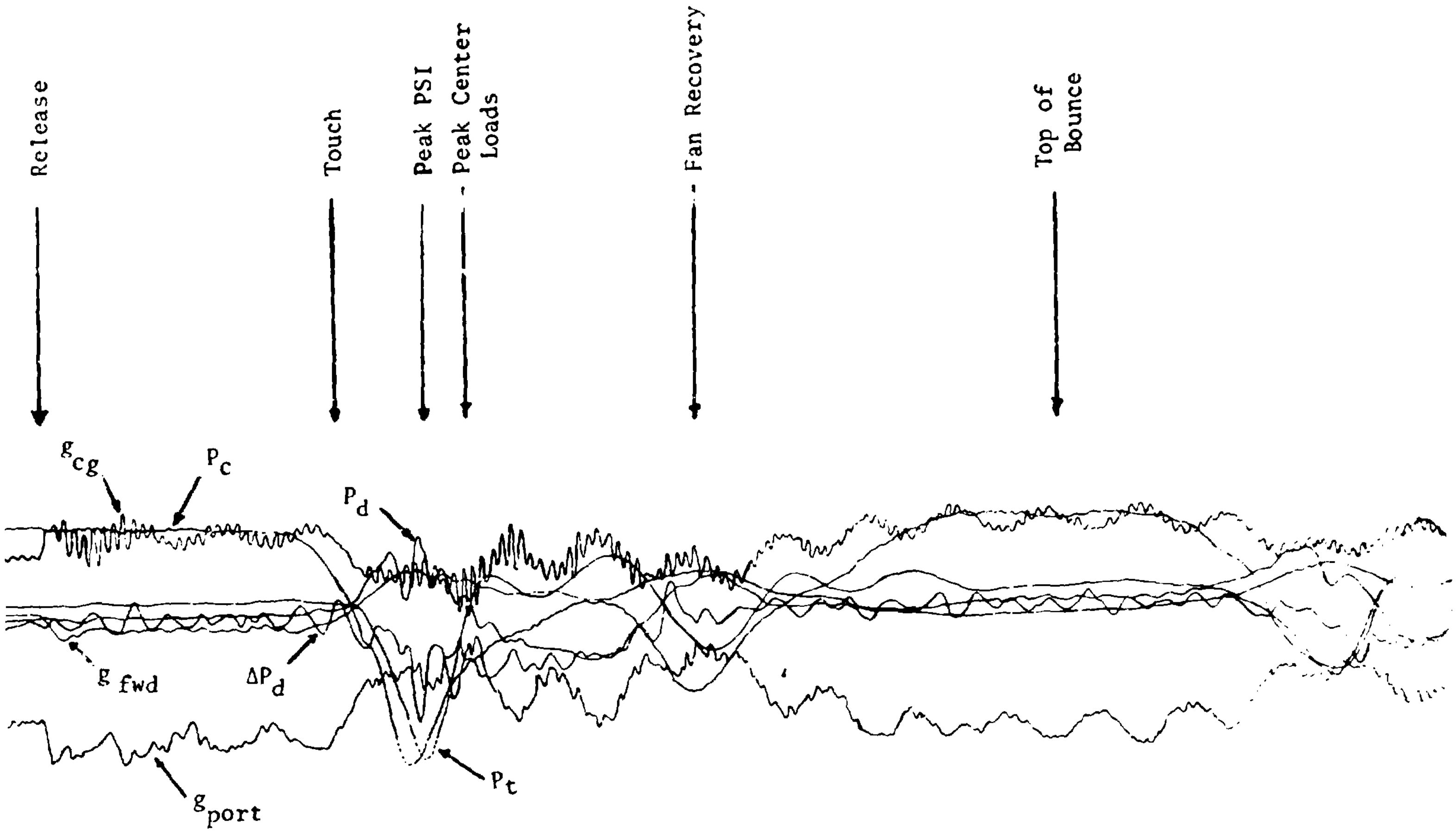

FIGURE 7 SIX CHARACTERISTIC EVENTS FOR A LEVEL LANDING (DROP NO. 8)

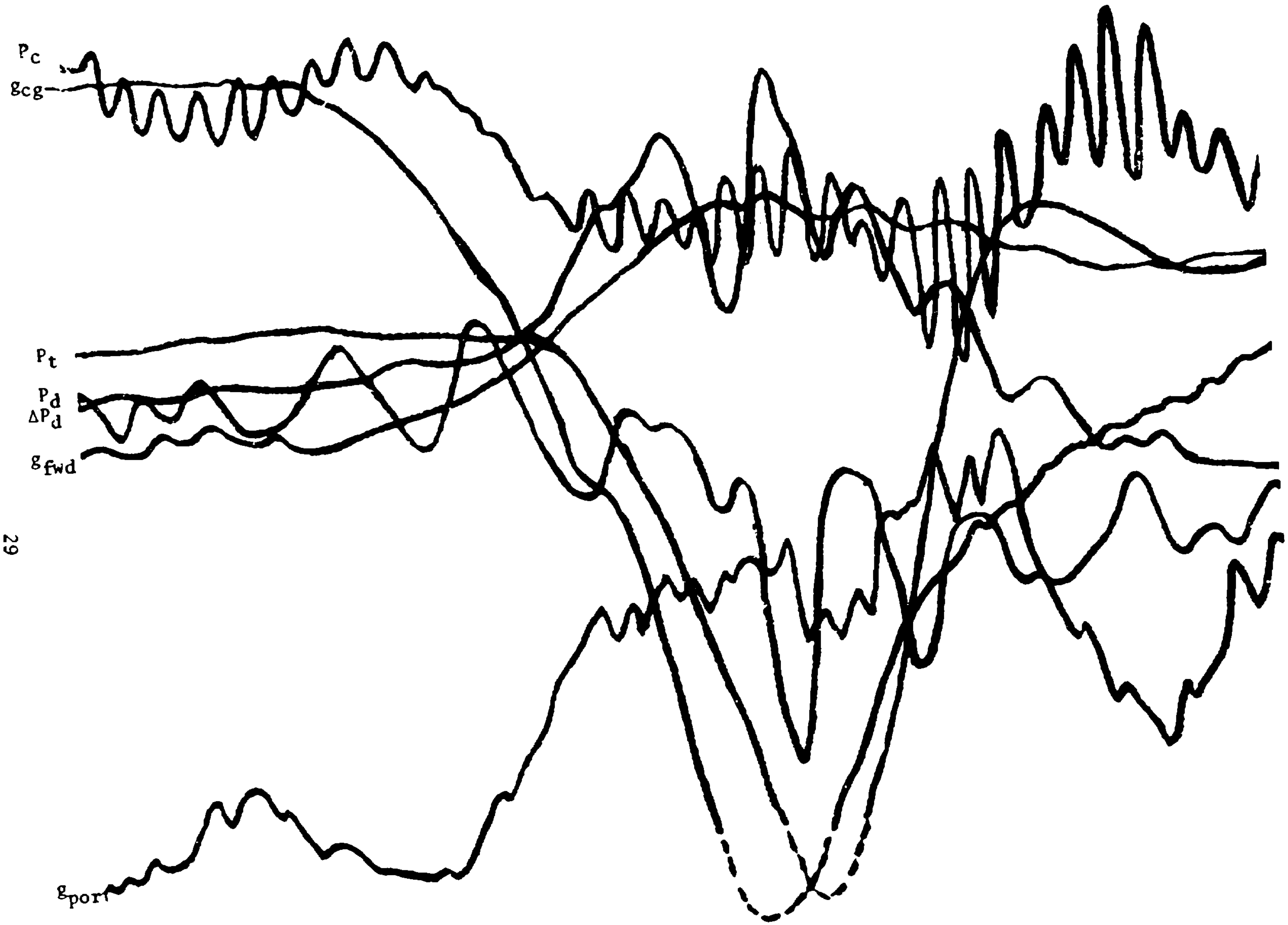

FIGURE 8. OSCILLOGRAPH DETAILS OF PEAK PRESSURES AND PEAK LOADS FOR A LEVEL LANDING

(d) Peak center loads -- are the maximum accelerations measured at the center of gravity and at the port accelerometer. These accelerations lagged the peak pressure event for all level landings. The time delay between peak pressure and peak loads was always short (about .024 to 0.03 seconds). This delay may be caused by the bag "bulging out" and flattening immediately following the cushion pressure buildup. This bulging out is very noticeable from the front view movies and results in a rapid increase in the trunk pressure contact area. It should be noted, however, that the g loads remain at a high level throughout the time between peak pressures and peak loads, which indicates an efficient energy absorption system.

(e) Fan recovery -- is the nominal time when the trunk and cushion pressures and the two diffuser pressures rise to second peaks. This event is caused by the fan coming out of stall while the vehicle is still in ground effect. The differential pressure goes from a negative to a positive value for the first time following the initial pressure peaks. This time interval of reverse flow through the diffuser was about 0.14 seconds for all the drop tests.

(f) Top of Bounce -- is estimated to occur at the midpoint of the time that the model was out of ground effect (minimum P_c) following the first impact.

The results of the three level drop tests (1, 2, and 8) are given in Tables 7, 8, and 12. The four pressures, three accelerations, and the time are noted for each of the six characteristic events -- giving a total of 48 data points for each level drop test.

The most important result to notice is that the peak pressures and the peak vertical accelerations were nearly the same -- despite the fact that the drop heights varied from 7.28 to 3.77 inches, simulating full scale sink speeds of 12.5 to 9.0 ft/sec. For the higher drop heights, the duration of the peak loads was longer because more vertical energy had to be absorbed. For each of these three tests, the peak trunk pressure was about 200 psfg and the peak total loads were about 2.6 g's (referenced to a zero g free fall).

The fan stall and backflow is therefore acting as an important mechanisn to limit the pressures and resulting loads. The strong influence of the fan stall is further indicated by the fan recovery loads. For these tests, the fan recovered while the model was still in ground effect. The resulting surge of flow caused a second pressure peak which gave loads of 2.1 g's. This is an undesirable effect since it can cause excessive model bouncing. Since these second peak loads occur after the landing system has already absorbed the vertical energy, the fan recovery acts to push the model upward at a time when the model has already bottomed out and is moving upward. Therefore, it may be desirable to have a longer fan recovery time or a slower fan recovery rate.

(2) Non-Level Drop Test Results.

Tests 5, 6, 7, and 11 were all non-level drops (non-zero pitch and roll angles). All of these tests except Number 7 did not have the same six characteristic events during the first bounce as did the level drop tests. The differences for tests with 10° pitch versus zero degrees initial pitch are as follows:

(a) Release -- was the same.

(b) Touch -- was the same.

(c) First Peak P_t. The diffuser pressure (P_d) and the trunk pressure (P_t) hit a peak at nearly the same time as a level drop. The differential pressure (P_d) does not always clearly peak, as it does in a level drop. ΔP_d will increase towards zero and may become negative (indicating backflow), but the peak backflow usually occurs later. The cushion pressure (P_c) remains nearly zero during this time of first peak trunk pressure, instead of peaking as it does in a level drop.

(d) Peak Loads. The vertical accelerations hit their peaks at the same time that P_t and P_d hit second peaks and that P_c hits its first peak. For 10° pitch, the time delay between first peak P_t and peak loads was 0.09 to 0.11 seconds. This is different from drops at zero degrees pitch -- where peak loads followed the first peak pressures by a short time span of 0.024 to 0.03 seconds. For 10° pitch, the value of ΔP_d could be positive or negative at the time of peak loads, since the time delay from first peak P_t is long enough to sometimes give the fan time to recover just before the first P_c peak.

(e) Fan Recovery. When the fan comes out of stall, the pressures peak just as they do in level drop tests. This event may occur at the same time as peak loads, as noted above. If the recovery occurs after peak loads, then it causes a third peak in the trunk pressure and a second peak P_c. Excessive bouncing results.

(f) Top of bounce -- was the same.

For the four non-level drops reported here, all the pressures peaked at the same time (as they do in a level drop) for all bounces after the first one.

The one non-level test (Number 7) with zero degrees pitch (and 7 1/2° roll) resulted in the P_c peak closely following the P_t peak. Therefore, there was only one clear pressure peak for the first bounce. This made this 7 1/2° roll impact similar to a level landing.

The results of the four non-level drop tests (5, 6, 7, and 11) are given in Tables 9, 10, 11, and 13. Figure 9 shows the oscillograph traces for a typical drop at 10° pitch (Test 11). Figure 10 shows a full scale close up of the first peak pressures of Test 11.

An important result to notice is that the cushion pressure is zero during the first peak trunk pressure, and that when the model does level out, the resulting cushion pressure peak causes second peaks in P_t and P_d, and also results in the peak vertical accelerations.

(3) Effect of Initial conditions.

The three initial conditions were drop height, pitch angle, and roll angle. The various tests can be compared to show the effect of these three parameters.

(a) Effect of drop height for level drops. Tests 1, 2, and 8 were level drops from 7.28, 5.64, and 3.77 inches, respectively. For these tests, there was clearly no increase in the peak loads as the drop height increased. This result is different from what one might intuitively expect, but it represents an efficient energy absorption system with respect to stroke. The peak loads were about 2.5 g's for each test (compared to a level of zero g for free fall). In fact, the highest loads were 2.7 and 2.9 g's on the port and c.g. accelerometers during the drop from the lowest of these three heights.

$P_t = 200$

During each drop, the four pressures reached the following approximate peaks: $P_c = 160$, $P_d \approx 155$, and $\Delta P_d = 45$ psf. The duration of the pressure and acceleration peaks was shortest for the test with the lowest drop height. The time from touch to peak pressures or loads was 0.05 to 0.09 seconds.

(b) Effect of drop height for an initial 10° pitch, 0° roll. Tests 5 and 11 were made from drop heights of 7.28 and 3.77 inches, respectively. In contrast to the level drop tests, the peak loads increased with increasing drop height for the tests at 10° initial pitch. In fact, the aft hard structure hit the plywood floor during Test 5, exerting 5.5 and 6.0 g vertical loads into the structure.

The angular accelerations were also greater at the higher drop height with 0.6 g differences between center and forward accelerometers being recorded as compared to 0.4 g differences for the lower heights. The angular acceleration can be calculated as a function of the difference between the forward and center of gravity accelerations:

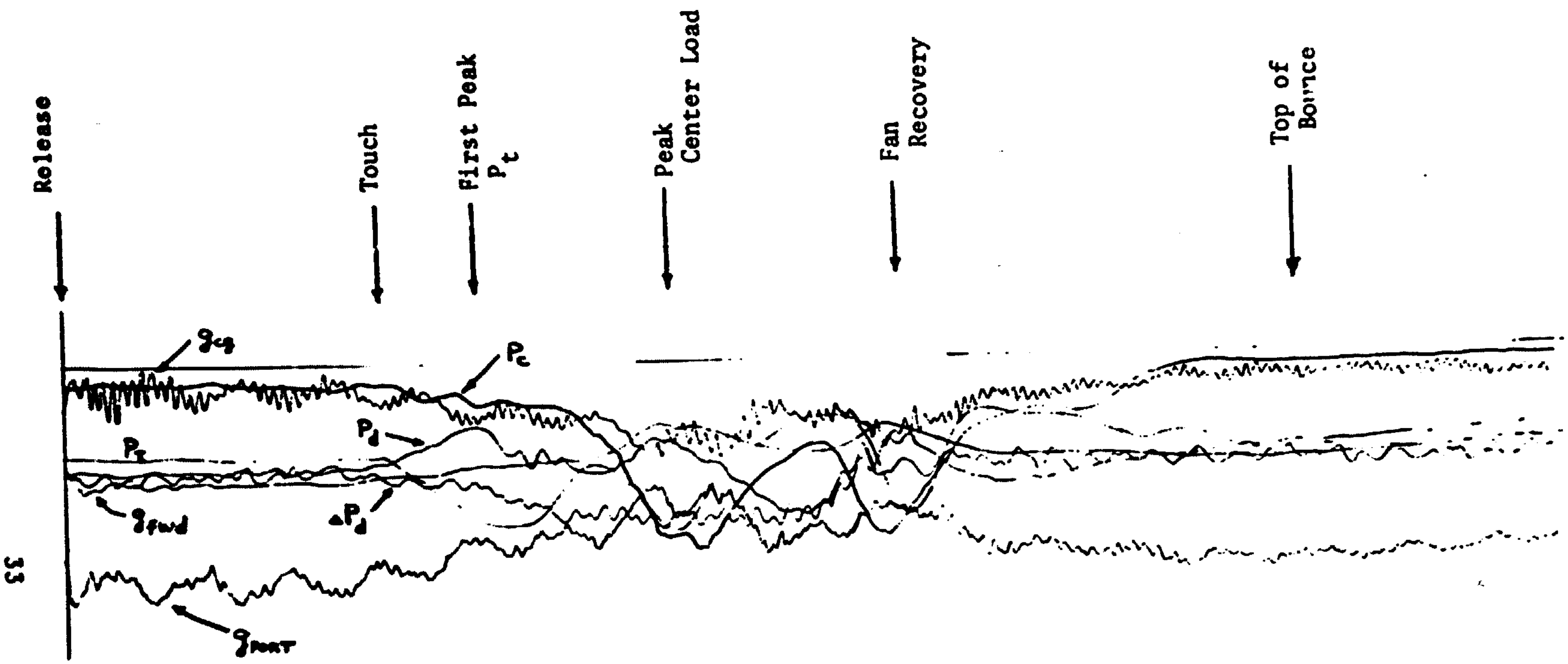

FIGURE 9. SIX CHARACTERISTIC EVENTS FOR A 10° PITCH LANDING (Drop No. 11)

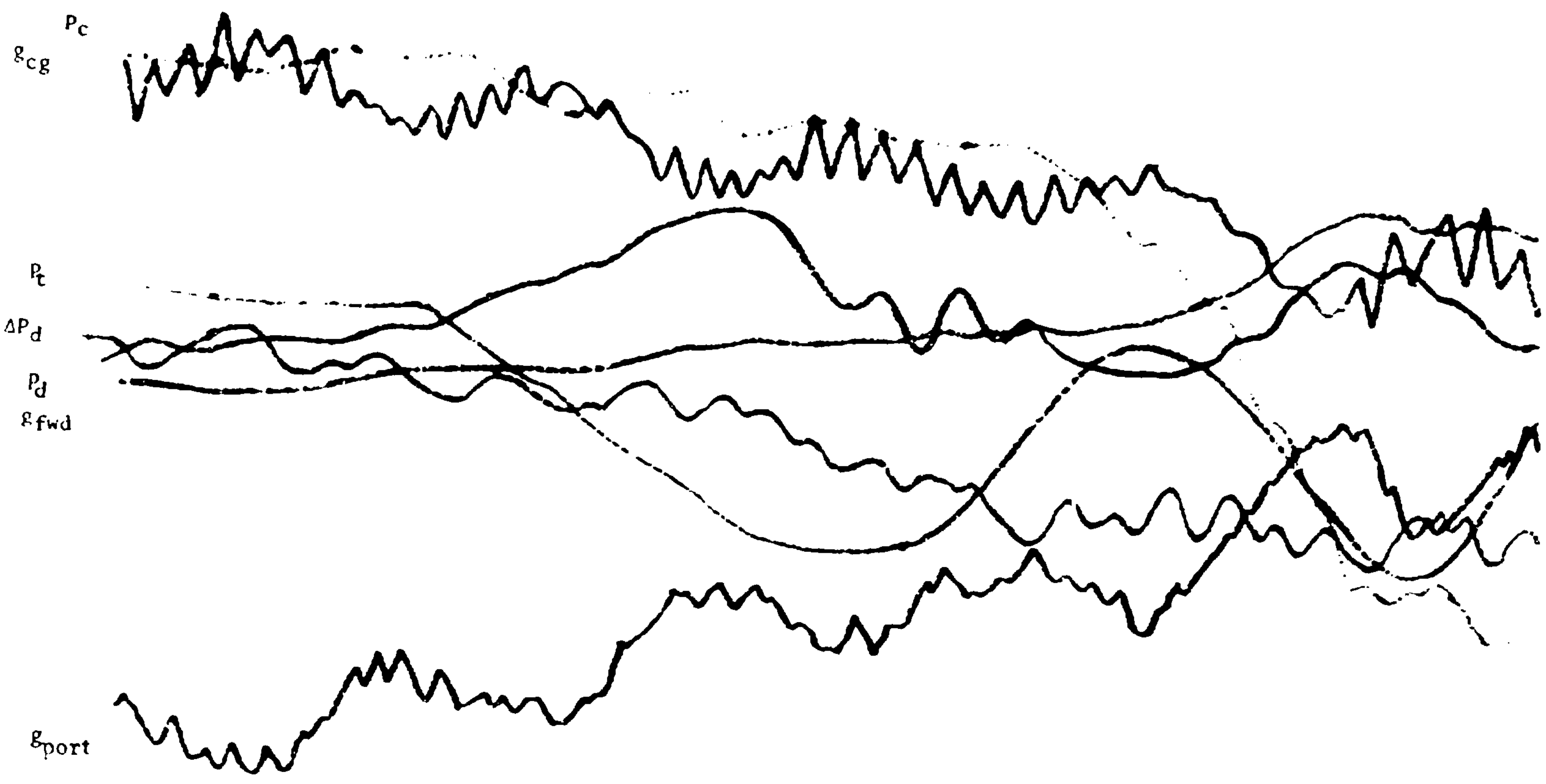

FIGURE 10. OSCILLOGRAPH DETAILS OF PEAK PRESSURES AND LOADS FOR A NOSE-UP LANDING (Drop No. 11)

$$\alpha(\text{radians/sec}^2) = \frac{(\ell\ \text{nose})(W_A)(g\ \text{cg} - g\ \text{fwd})}{I_{yy}}$$

where ℓ nose was 3.42 ft.

If I_{yy} = 270 slug ft^2, then α = 7.73 (g cg - g fwd)

(c) Effect of Pitch angle. Tests 8 and 11 were identical except that the pitch angle was zero and 10°, respectively. The non-zero pitch angle resulted in lower pressure peaks and lower vertical loads. This was in spite of the fact that the actual maximum sink speed was higher since the model continued to accelerate after the aft trunk touched. From the limited data gathered, it appeared that the peak angular accelerations did not differ significantly with pitch angle. This result should be examined further. Even when the cushion pressure returned to zero on the first bounce following nose up landing, P_t and P_d remained higher than normal because the forward trunk was still in ground effect.

The above conclusions about the effect of pitch angle on peak vertical and angular accelerations are drastically reversed if the hard structure hits. Tests 1 and 5 demonstrate this. Although dropped from the same height, the aft hard structure hit in Test 5, resulting in very large accelerations (6 g's).

One significant observation from the 10° initial pitch test was that the maximum pitch angle was not the initial one. From the movies of both the Bell tests (with wing lift) and these tests (without lift), it was clear that the maximum pitch angle occurred during the first bounce and was a negative value (nose down). This was substantiated in Test 11 which was dropped at +10° but reached -13° on the first bounce. The hard structure did not hit in the front, only because it was not extended to simulate the full scale model. A true scale model would have the forward hard structure extend about 50% further beyond the trunk than the aft hard structure. Aerodynamic (elevator) control appears necessary to prevent the forward hard structure from hitting the landing surface following hard, nose up landings.

(d) Effect of roll angle. Tests 2 and 7 were identical except that the initial roll angle was 0° and 7 1/2°, respectively. Although the peak pressures were higher for the level drop, the peak accelerations were highest for the landing at 7 1/2° roll. The peak vertical loads were about 2.6 g for level landing versus 3.0 g for the landing with roll. This is because the level landings cause the fan to quickly stall before the maximum trunk contact area occurs. At 7 1/2° roll, there had not been as much backflow through the fan before the peak load occurred. Also, the trunk volume at the time of peak loads was less. Therefore, the trunk pressure was higher at peak load for the landing with non-zero roll (135 psf versus 98 psf). A non-zero angle does not significantly change the characteristic events as does non-zero pitch angle.

The initial roll angle is not taken out during the first bounce. The roll angle at the top of the first bounce (0.83 seconds after release) was equal to the initial roll angle (7 1/2°). The roll angle passed through zero degrees at 1.10 seconds after release.

Vibrations of the trunk were more noticeable in the films of Test 7 than any other test.

V. MAJOR FINDINGS

A. The model was not geometrically similar. Most important, the hard structure did not extend immediately forward of the trunk. The model was not dynamically similar since the trunk was not elastic and did not incorporate flow trim valves. Also, the wings were not modeled similar with respect to shape, aerodynamic damping, or elasticity.

B. The one-way flow diaphram did not function properly, since it restricted the normal flow at the diaphram instead of at the aft trunk holes. The diaphram was therefore removed for all static and drop tests.

C. Static load deflection tests showed identical results when weights were added to the center of pressure (model level) instead of to the center of gravity (model nose high). The portion of the load supported by the trunk increased from 3% to 24% as the total model weight was increased from 610 to 1310 lbs (assuming a constant cushion area). Above 1310 lbs to the trunk pressure exceeded 105 psfg and the fan stalled. The model deflected one inch when 560 lbs were added to it during hover over a solid surface.

D. Noise throughout the test cell was 112 db.

E. Six characteristic events were noted for all hard level landings: (1) release (start of free-fall), (2) touch (model enters ground effect), (3) peak pressures, (4) peak loads at center of model, (5) fan recovery from stall, (6) top of bounce. A similar six events occurred for all landings at 10° pitch. The biggest difference of the nose up landing from level landings is that the cushion pressure does not peak until the time of peak loads.

F. Three critical landing conditions were observed: (1) The aft hard structure hit the surface during a hard landing with nose up (Test 5), (2) The peak vertical loads at a given sink speed occurred during a 0° pitch landing with 7 1/2° initial roll angle (Test 7), (3) The forward hard structure could hit the surface following a hard landing with nose up and then rotation on to the nose. This negative (nose down) pitch angle can exceed the initial pitch angle (-13° versus +10° on Test 11).

G. The excessive bouncing of the quarter scale is caused by fan recovery (and resulting pressure and load spikes) which occurs after the downward vertical energy has been absorbed.

H. Peak vertical loads of 2.6 g's (referenced to a zero g free-fall) were measured on all level drops which simulated a full scale sink speed of 9.0 to 12.5 ft/sec (Tests 1, 2, and 8).

I. The effects of the three initial conditions (drop height, pitch angle, and roll angle) were determined. Increasing drop height caused an increase in both vertical and angular accelerations for tests at 10° pitch, while no load increase was observed for tests at 0° pitch. Increasing pitch angle did not increase the loads, but did decrease the hard structure clearance -- both aft and forward. A 7 1/2° roll angle caused higher loads than a landing at zero roll (3.0g for Test 7 versus 2.6g for Test 2).

VI. CONCLUSIONS

A. Further ACLS model testing is necessary in order to better understand the characteristics of the system. Without a better understanding of the characteristics, very few design improvements will be possible. These limited tests showed several important characteristics including: (1) the efficient energy absorbtion characteristics during level landing at various sink speeds, and (2) the unfavorable characteristics of non-zero roll angle, fan recovery, and forward hard structure clearance.

B. Better dynamic model prediction techniques are necessary. No computer model developed to date has predicted the characteristics reported here. The computer model used for the Advanced Development Program takes an extremely long time to run and has not been developed to predict events beyond the first pressure peaks. This program is not satisfactory for use with an aircraft equation of motion simulation.

C. The stall and recovery characteristics of the air supply system (fan) have a major effect on the landing system characteristics. Jet ejectors should therefore be investigated in model tests since ejectors have been proposed recently for certain ACLS uses. Tip fans should also be considered in cases where a high pressure air supply is available (compressor bleed) and yet a high augmentation ratio is necessary -- beyond the range where a jet ejector is efficient.

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